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**Timber Trade Restrictions and Tropical Deforestation:  
A Forest Mining Approach**

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# TIMBER TRADE RESTRICTIONS AND TROPICAL DEFORESTATION: A FOREST MINING APPROACH

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## ABSTRACT

Timber trade restrictions have been proposed as a means to reducing tropical deforestation. This paper analyses the consequences of such trade interventions, emphasising the effects on logging behaviour and the allocation of land between forestry and alternative activities (e.g., agriculture). Tropical forestry is modelled as the mining of a heterogeneous, non-renewable resource. Two different harvesting procedures – *sequential* and *simultaneous* harvest – are examined. The analysis suggests that logging will be reduced if timber trade restrictions reduce the log price equally for all tree qualities. But if the price reduction is non-uniform, logging may increase in some fields. In fact, total logging may increase as well. It is also shown that timber trade restrictions do not necessarily promote the conversion of forestland to alternative uses.

*Key words:* Tropical forest, deforestation, mining, trade policy.

*JEL classification:* F13, Q23, Q24, Q28.

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## **1. Introduction\***

The World Commission on Environment and Development identified the international trade in tropical timber as one of the causes of tropical deforestation (WCED, 1987). Timber trade restrictions have therefore been proposed in several countries as a means of retarding the rate of tropical deforestation (ITTO, 1993).

The idea behind the use of timber trade restrictions is simple: by reducing timber prices, logging will be reduced, and the rate of deforestation will slow down. This argument has been challenged on at least three accounts, however: (1) It is false because it ignores that forestland has alternative uses. To make forestry less profitable may in fact accelerate the rate of deforestation by promoting the conversion of forestland to agricultural or industrial uses. (2) The argument might be correct if there were substantial trade in tropical timber. But since only a small share of tropical timber and timber products is exported, trade restrictions will not be effective. (3) Although trade provisions may have some desirable effects, they are clearly an inefficient means of environmental protection in this context, because the environmental problems at issue are caused by timber extraction, and not by timber trade as such.

The latter objection is a general, and valid, criticism against the use of trade policy for environmental purposes. Trade policy is not a first best instrument for environmental regulation unless trade is the direct source of environmental degradation. However, in the case of transborder environmental problems, it is far from obvious that first best policies ever will be implemented. The use of trade measures by the victim countries may then be a second best policy alternative (Markusen (1975), Rauscher (1991), Mæstad (1998)). Since tropical forests provide global environmental benefits (e.g., biodiversity protection and carbon storage), the local governments lack the incentives to implement efficient environmental regulations. Timber trade restrictions in importing countries can be understood as a second best policy in reply to such policy failures. It is beyond the scope of this paper to address the overall efficiency

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aspects of timber trade policies; our present concern will only be with their consequences for tropical deforestation.

Consider next the objection that trade in tropical timber is so limited that trade restrictions will be ineffective. According to FAO, only 14% of tropical timber production was exported in 1990 (ITTO, 1993). But these aggregate numbers conceal substantial regional differences. While the export from Brazil is negligible, substantial volumes are exported from Indonesia and other South-East Asian countries. Therefore, even though trade restrictions will be ineffective in some regions, they may work fairly well in others. By way of illustration, Barbier *et.al* (1995) found that an import ban would reduce Indonesian log production by 28%, sawnwood production by 11%, and plywood production by 44%.

The prevailing view about the effect of timber trade restrictions on tropical deforestation is that, on one hand, logging will decline due to lower timber prices, but that, on the other hand, reduced profitability in forestry will encourage the conversion of forestland to alternative uses (e.g., Vincent (1990), Grainger (1993), ITTO (1993), Swanson (1993), Barbier and Rauscher (1994), von Amsberg (1998)).

This article provides partial support for these claims but questions their general validity. A notable difference from previous contributions is the emphasis placed on the modelling of logging behaviour in this paper. Logging is modelled as the mining of a heterogeneous, non-renewable resource, and a sequential harvest model is developed in order to take into account that loggers may want – or may be told by public authorities – to finish logging in one area before proceeding to the next. The model is related to Cairns (1986) and Krautkraemer (1989), who analyse the mining of a heterogeneous mineral ore, but the model is adapted to the particular setting of a tropical forest and is extended by taking into account additional types of heterogeneity of the resource. Mining models have also been used to analyse the drawdown of old-growth timber stands (e.g., Brazee and Southgate (1992), Berck (1979), Brown and Wong (1993), Lyon (1981), Lyon and Sedjo (1983), and Brazee and Mendelsohn (1990)). For our

purposes, a major shortcoming of these contributions is the failure to recognise the heterogeneity of old-growth timber stands in the tropics.

The analytical framework is outlined in Section 2. In Section 3, two different logging models are developed, and the effect of timber trade restrictions on logging behaviour is examined. The effect of lower timber prices on the allocation of land between forestry and alternative uses is discussed in Section 4. Section 5 concludes.

## **2. The analytical framework**

Commercial logging is of crucial importance for the rate of tropical deforestation, especially in South East Asian countries. Besides the direct impact of logging on the rate of deforestation, commercial logging plays an important indirect role by making the logged areas accessible to shifting cultivators who utilise the forest land for agricultural purposes (Amelung and Diehl (1992), ITTO (1993)). In order to predict the effect of timber trade restrictions, it is therefore crucial to understand the behaviour of the logging companies.

Tropical forestry differs from forestry in temperate regions in several respects. First, tropical forestry is often conducted with a short time horizon, because the duration of timber concessions is generally very short. Poore *et.al* (1989) and Grainger (1993) report that concessions are issued for periods of 20-25 years, with no guarantee of renewal. Given the short time horizon, the logging companies cannot be expected to pay much attention to the fact that the forest is a growing resource. Hence, it seems appropriate to model logging behaviour as the mining of a non-renewable resource.

Secondly, tropical forests are characterised by much greater heterogeneity than timber plantations in temperate regions. Within each logging field there is heterogeneity due to the large number of different tree species and the corresponding differences in tree qualities. Furthermore, some areas in the tropical forests are far less accessible than others. This creates substantial heterogeneity among various logging fields through differences in harvest costs.

Our framework differs from previous literature on the mining of heterogeneous non-renewable resources by capturing both these types of heterogeneity in one model.<sup>1</sup> First, we allow for more than one logging field and different harvest costs across fields. The field specific marginal harvest costs in field  $i$  ( $\bar{c}^i$ ) are assumed constant, and the fields are indexed so that  $\bar{c}^i \leq \bar{c}^{i+1}$ . Secondly, we allow tree quality within each field to be heterogeneous in the sense that the loggers receive different prices for different trees. Each logging field contains  $\bar{H}$  trees, and the quality distribution is assumed to be the same in all fields.<sup>2</sup>

Besides tree quality, timber prices depend on the prevailing trade policy regime. Restrictions on the trade in tropical timber and timber products imposed by importing countries reduce the demand for tropical timber and are assumed to reduce timber prices. Let the parameter  $\alpha$  represent the prevailing trade policy regime, and let trade restrictions appear as a negative shift in  $\alpha$ . Now, define the function  $p = p(H, \alpha)$  as the price of the  $H$ th most valuable tree in a logging field.  $H$  will be treated as a continuous variable on the interval  $[0, \bar{H}]$ . The assumed properties of the price function are  $p_H < 0$  and  $p_\alpha > 0$ .

Timber prices are exogenous for each individual logging company. Profit-maximising loggers with a positive discount rate will then finish all harvest immediately after the concession is opened unless marginal harvest costs increase with the total harvest per period or timber prices are expected to rise over time. In this paper, it will be assumed that logging companies expect timber prices to remain constant, and that marginal harvest costs increase with the total harvest per period.<sup>3</sup> The increase in harvest costs may reflect, e.g., that the logging capacity is limited and that the operating costs increase disproportionately as one approaches the capacity ceiling. Capacity limits may also exist in the timber transportation network or in the downstream

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<sup>1</sup>Hartwick (1978) assumes that extraction costs differ among deposits/fields but that the quality of the resource itself is homogeneous. In Cairns (1986) and Krautkraemer (1989), resource quality is heterogeneous, but there is only one deposit/field.

<sup>2</sup>In effect, we assume that there are many identical fields, each with a different access or transportation cost. The assumption that all fields are of equal size simplifies the mathematical exposition, but it is not restrictive since a large logging field can be thought of as several smaller fields with identical harvest costs.

<sup>3</sup>In von Amsberg (1998), an increasing price path is assumed. That is a common assumption in models with non-renewable resources, because the scarcity of a non-renewable resource will tend to increase over time. However, such an approach does not seem satisfactory here, despite the fact that we model tropical forestry as the mining of a non-renewable resource. The fact that myopic logging companies *perceive* the forest as a non-renewable resource, does of course not imply that the forest is *de facto* non-renewable. The rationale for assuming a rising price path is thus less obvious here than in a traditional non-renewables model.

timber processing industry. The capacity utilisation costs will be represented by the function  $c = c(\sum_i h_t^i)$ , where  $h_t^i$  is the number of trees harvested in field  $i$  at time  $t$ , and where  $c' > 0$  and  $c'' > 0$ . Note that the capacity utilisation costs come in addition to the field-specific harvest costs. The discounted profit of a logging company can now be written as

$$\pi = \int_0^{\bar{T}} \left[ \sum_i (R_t^i - \bar{c}^i h_t^i - c(\sum_i h_t^i)) \right] e^{-rt} dt, \quad (1)$$

where  $\bar{T}$  is the length of the concession period,  $R_t^i$  is the revenue collected from field  $i$  at time  $t$ , and  $r$  is the discount rate.

### 3. Timber trade restrictions and logging behaviour

In the special case when the discount rate is zero and the time constraint (i.e., the length of the concession period) is non-binding, profit maximising logging companies will harvest all trees for which price exceeds marginal harvest cost. Moreover, the loggers will be indifferent with respect to the order in which the trees are harvested.

When future profit is discounted, it is profitable, *ceteris paribus*, to begin with the trees that contribute most to profits. Since each logging field contains both low valued and high valued species, the loggers may therefore want to shift their logging activity back and forth among fields. Without any economies of scale in logging, they would in fact disperse their efforts across all profitable logging fields and log the fields simultaneously. Such a harvest pattern will in the following be called *simultaneous harvest*. However, to always first pick the most valuable tree may cause considerable damage to the other trees in the field, in particular if heavy machinery is utilised. It might therefore be more profitable to harvest the trees in the same order as they appear when the loggers proceed through a logging field. In that case, it will pay to completely finish the harvest in a low cost field before moving on to less profitable logging fields. Such a harvest pattern will be called *sequential harvest*. In most areas, sequential harvest is probably closer to the actual harvest pattern than simultaneous harvest. Most of our attention will therefore be devoted to a model of sequential harvest. But since it is



sometimes observed that logging companies move their activities back and forth among different fields, a simultaneous harvest model will be discussed as well.

### 3.1 Sequential harvest

Moving around in a forest in order to harvest more valuable trees before less valuable trees may impose huge damage on the remaining forest. If the costs of such forest destruction are greater than the gains from always picking the most valuable trees first, it is profitable to harvest the forest sequentially, finishing logging in one field before moving on to the next. Sequential harvest may also be chosen if the opening of new logging fields involves fixed set-up costs (e.g., the building of new roads) (see Hartwick *et.al* (1986)). And in some countries (e.g. Indonesia), the loggers are instructed by public authorities to harvest sequentially.

The desire to avoid forest damage is taken as the point of the departure of the sequential harvest model formulated here. It is therefore assumed that within each logging field in the sequence, the trees are harvested in order of appearance, not in order of quality.<sup>4</sup>

Without loss of generality, it will be assumed that there are only two logging fields. Let  $T^i$  denote the time used on field  $i$ . The present value of the concession can then be written as

$$\pi = \int_0^{T^1} [R_t^1 - \bar{c}^1 h_t^1 - c(h_t^1)] e^{-rt} dt + \int_{T^1}^{T^1+T^2} [R_t^2 - \bar{c}^2 h_t^2 - c(h_t^2)] e^{-rt} dt . \quad (2)$$

The number and quality of the trees harvested determine the loggers' income at any point of time. For a given number of trees, the loggers may increase the average quality of the harvest by logging in a larger area. Let  $a_t^i \in [0,1]$  represent the share of the total area in logging field  $i$  that is logged at time  $t$ , i.e. *the area depletion rate*. For simplicity, assume that trees of a given quality are uniformly dispersed within each logging field. Then, the income from harvesting the  $h$  most valuable trees from a fraction  $a$  of the field equals  $a$  times the income from harvesting the  $h/a$  most valuable trees from the entire logging field. The income from logging in field  $i$  at time  $t$  can thus be written as

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<sup>4</sup>The inability to return to low quality trees at a later point of time resembles the mining models of Cairns (1986) and Krautkraemer (1989). However, if the fields are harvested sequentially due to fixed set-up costs, it might be more appropriate to assume that the trees are harvested in order of quality within each field.

$$R_t^i = R(h_t^i, a_t^i, \alpha) = a_t^i \int_0^{h_t^i/a_t^i} p(h, \alpha) dh. \quad (3)$$

### 3.1.1 The concession period - a binding constraint

If the concession period is a binding constraint (i.e.,  $T^1 + T^2 = \bar{T}$ ), the decision problem of the logging company can be formulated as a two-step procedure: (1) Find the optimal time paths  $\{h_t^{i*}, a_t^{i*}\}$ ,  $i = 1, 2$ , for a given  $T^1$  (the switching date), and (2) find the optimal switching date.

For a given switching date, the loggers will choose the time paths of the harvest volume and the area depletion rate in any of the fields so as to

$$\text{Maximise } \int_0^T [R(h_t, a_t, \alpha) - \bar{c}h_t - c(h_t)] e^{-rt} dt \quad (4)$$

$$\text{s.t.: } H_0 = 0, \dot{H} = h_t, H_T \leq \bar{H}, h_t \geq 0, A_0 = 0, \dot{A} = a_t, A_T \leq 1, a_t \geq 0, \quad (5)$$

where  $H_t$  is the total number of harvested trees in the field up to time  $t$  and  $A_t$  is the share of the field area that has been depleted up to time  $t$ . The current value Hamiltonian is

$$\mathcal{H} = R(h_t, a_t, \alpha) - \bar{c}h_t - c(h_t) - \lambda_t a_t - \gamma_t h_t, \quad (6)$$

where  $\lambda_t$  and  $\gamma_t$  are the current value user cost associated with the scarcity of the available forest resources. An interior solution requires

$$\begin{aligned} R_h - \bar{c} - c' - \gamma &= 0, & \dot{\gamma} &= r\gamma, \\ R_a - \lambda &= 0, & \dot{\lambda} &= r\lambda. \end{aligned} \quad (7)$$

These are the standard static and dynamic efficiency conditions. The harvest volume is chosen so that marginal income equals marginal harvest costs, including the user cost associated with the finite number of trees in the field. Note that the transversality condition on  $H_T$  requires that  $\gamma_T \geq 0$  and  $e^{-rT} \gamma_T (\bar{H} - H_T) = 0$ ; either all trees are harvested at the end of the time horizon, or the user cost is zero. We will assume that there are always some trees in the field that do not have a positive commercial value, i.e.  $p(\bar{H}, \alpha) < \bar{c}^i$ . These trees will not be

harvested, implying that  $\bar{H} > H_T$  and  $\gamma_T = 0$ .<sup>5</sup> Eq. (7) then implies that  $\gamma$  is always zero. The conditions for an interior solution can therefore be rewritten as

$$\begin{aligned} R_h - \bar{c} - c' &= 0, \\ R_a - \lambda &= 0, \quad \dot{\lambda} = r\lambda. \end{aligned} \quad (8)$$

All dynamic considerations are captured through the choice of the area depletion rate. For a given area depletion rate, the harvest rate is chosen so as to equal marginal revenue and marginal harvest costs. Note that since there are no costs related to area depletion as such in the model, it will always be optimal to log in the whole field area, i.e.  $A_T = 1$ . The dynamics of the area depletion rate and the harvest rate can now be found by differentiating Eqs. (8),

$$\dot{a} = \frac{rR_a}{R_{aa}} - \frac{rR_a}{c''} \left( \frac{a}{h} \right)^2, \quad \dot{h} = -\frac{rR_a}{c''} \frac{a}{h}. \quad (9)$$

Differentiation of Eq. (3) with respect to  $a$  gives  $R_a > 0$  (to harvest a given number of trees from a larger area implies higher average quality) and  $R_{aa} < 0$ , implying that  $\dot{a} < 0$  and  $\dot{h} < 0$ . Moreover, it can be shown that  $h/a$  increases over time, i.e., the average quality of the harvest is declining.<sup>6</sup> In other words, it is optimal to tilt the harvest of high quality trees towards the present. This is achieved by starting out with a high area depletion rate in each field.

We have found the optimal time paths  $\{h_t^{i*}(T), a_t^{i*}(T)\}$  as functions of the switching date  $T$ .

The optimal switching date in the two field model can now be found as the solution to:

$$\max_T \left\{ \int_0^T [R(h_t^{1*}(T), a_t^{1*}(T), \alpha) - \bar{c}^1 h_t^{1*}(T) - c(h_t^{1*}(T))] e^{-rt} dt + \int_T^{\bar{T}} [R(h_t^{2*}(T), a_t^{2*}(T), \alpha) - \bar{c}^2 h_t^{2*}(T) - c(h_t^{2*}(T))] e^{-rt} dt \right\}, \quad (10)$$

subject to  $T \in [0, \bar{T}]$ . The first order condition for an interior solution is

<sup>5</sup>According to Grainger (1993), only between two and ten trees out of a total of over 350 are felled and removed per hectare.

<sup>6</sup>Differentiation of  $h/a$  with respect to time gives  $\text{sgn}(d(h/a)/dt) = \text{sgn}(ha - ah)$ . By using the expressions in Eq. (9), we obtain  $\text{sgn}(d(h/a)/dt) = \text{sgn}(-rhR_a/R_{aa}) > 0$ .

$$\begin{aligned}
& \left[ R(h_T^{1*}, a_T^{1*}, \alpha) - \bar{c}^1 h_T^{1*} - c(h_T^{1*}) \right] e^{-rT} - \left[ R(h_T^{2*}, a_T^{2*}, \alpha) - \bar{c}^2 h_T^{2*} - c(h_T^{2*}) \right] e^{-rT} \\
& + \int_0^T R_a \frac{\partial a_t^{1*}}{\partial T} e^{-rt} dt + \int_T^{\bar{T}} R_a \frac{\partial a_t^{2*}}{\partial T} e^{-rt} dt = 0.
\end{aligned} \tag{11}$$

From Eqs. (8) it can be shown that  $R_a e^{-rt} = \lambda_t e^{-rt}$  (a constant). Furthermore, because it is optimal in an interior solution to harvest from the whole field area in both fields, i.e.,  $\int_0^T a_t^{1*} dt = \int_T^{\bar{T}} a_t^{2*} dt = 1$ , we have that  $\int_0^T \partial a_t^{1*} / \partial T dt = -\partial a_T^{1*}$  and  $\int_T^{\bar{T}} \partial a_t^{2*} / \partial T dt = a_T^{2*}$ . Hence,

Eq. (11) can be rewritten as

$$R(h_T^{1*}, a_T^{1*}, \alpha) - \bar{c}^1 h_T^{1*} - c(h_T^{1*}) - \lambda_T a_T^{1*} = R(h_T^{2*}, a_T^{2*}, \alpha) - \bar{c}^2 h_T^{2*} - c(h_T^{2*}) - \lambda_T a_T^{2*}. \tag{12}$$

Eq. (12) says that the switching date should be chosen so that the Hamiltonian is continuous at time  $T$  (i.e.,  $\mathcal{H}^1(T) = \mathcal{H}^2(T)$ ). Now, by using Eq. (3) to find an explicit expression for  $R_a$  and using the condition  $R_a = \lambda$ , we can write  $R_T - \lambda_T a_T = h_T p(h_T/a_T, \alpha)$ . Hence, Eq. (12) can be written as

$$\left[ p(h_T^{1*}/a_T^{1*}, \alpha) - \bar{c}^1 \right] h_T^{1*} - c(h_T^{1*}) = \left[ p(h_T^{2*}/a_T^{2*}, \alpha) - \bar{c}^2 \right] h_T^{2*} - c(h_T^{2*}). \tag{13}$$

This expression can be further simplified by realising that the harvest rate is continuous over time, implying that  $h_T^{1*} = h_T^{2*}$ .<sup>7</sup> Eq. (13) can therefore be simplified to

$$p(h_T^{1*}/a_T^{1*}, \alpha) - \bar{c}^1 = p(h_T^{2*}/a_T^{2*}, \alpha) - \bar{c}^2. \tag{14}$$

$p(h_T/a_T, \alpha)$  is the price of the poorest tree quality harvested at time  $T$ . Then, what Eq. (14) is saying is that at the optimal switching date  $T$ , the price difference between marginal trees should equal the difference between the (constant) marginal harvest costs.

### 3.1.2 The concession period - a non-binding constraint

When the concession period is non-binding, the harvest pattern in the last field in the sequence is independent of the logging pattern in previous fields. Moreover, an additional transversality

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<sup>7</sup>A formal proof can be developed by substituting the first order condition for optimal harvest from Eq. (8), which says that  $p(h/a, \alpha) - \bar{c} = c'$ , into Eq. (13), and then utilising that  $c'' > 0$ . Details can be obtained from the author on request.

condition requires that the marginal profit of depletion is equal to the average profit of depletion at the chosen terminal time, i.e.,

$$\mathcal{H}(T^2) = R(h_{T^2}^2, a_{T^2}^2, \alpha) - \bar{c}^2 h_{T^2}^2 - c(h_{T^2}^2) - \lambda_{T^2} a_{T^2}^2 = 0. \quad (15)$$

By using Eq. (3) to find an explicit expression for  $R_a$  and using the condition  $R_a = \lambda$ , Eq. (15) can be rewritten as

$$[p(h_{T^2}^2/a_{T^2}^2, \alpha) - \bar{c}^2] h_{T^2}^2 - c(h_{T^2}^2) = 0. \quad (16)$$

The first order condition for optimal harvest at time  $T^2$  is  $p(h_{T^2}^2/a_{T^2}^2, \alpha) - \bar{c}^2 = c'(h_{T^2}^2)$  (see Eqs. (8) and (3)). Eq. (16) can therefore be rewritten as  $c'(h_{T^2}^2) h_{T^2}^2 = c(h_{T^2}^2)$ . Given the assumption that  $c'' > 0$ , this equation holds if and only if  $h_{T^2}^2 = 0$ . The optimal harvest pattern at the terminal time is then given by (see Eqs. (8))

$$p(h_{T^2}^{2*}/a_{T^2}^{2*}, \alpha) - \bar{c}^2 = 0. \quad (17)$$

In the limit, as one approaches the terminal time of field 2, it is optimal to harvest all trees with price above the field specific marginal harvest cost.

The optimal time used in field 1 is found as the solution to the following problem

$$\max_{T^1} \left\{ \int_0^{T^1} [R(h_t^{1*}, a_t^{1*}, \alpha) - \bar{c}^1 h_t^{1*} - c(h_t^{1*})] e^{-rt} dt + \pi^{2*}(\alpha) e^{-rT^1} \right\}, \quad (18)$$

where  $\pi^{2*}(\alpha)$  is the present value at time  $T^1$  of the total profit obtained from field 2 in optimum. The first order condition for an interior solution can be expressed as

$$R(h_{T^1}^{1*}, a_{T^1}^{1*}, \alpha) - \bar{c}^1 h_{T^1}^{1*} - c(h_{T^1}^{1*}) - \lambda_{T^1} a_{T^1}^{1*} = r\pi^{2*}(\alpha), \quad (19)$$

which is equivalent to

$$[p(h_{T^1}^{1*}/a_{T^1}^{1*}, \alpha) - \bar{c}^1] h_{T^1}^{1*} - c(h_{T^1}^{1*}) = r\pi^{2*}(\alpha). \quad (20)$$

The intuition is straightforward; the optimal time to spend in field 1 is such that the value of staying any longer in field 1 equals the cost of postponing the realisation of the profit from the subsequent field.

### *3.1.3 Timber trade restrictions*

We want to investigate the effect of timber trade restrictions on the optimal harvest pattern in these models. For this purpose, we will use numerical simulation. (Some analytical results are derived in the Appendix under the assumption that the logging capacity per period is fixed.) *A priori*, we expect that timber trade restrictions will reduce timber prices and that lower timber prices will reduce the optimal harvest. The exact effect of timber trade restrictions on timber prices will depend both on market characteristics (e.g., elasticities of demand and supply for the various species) and on the particular shape of the trade restrictions (e.g., whether or not the trade provisions discriminate between different species). The fact that the price reductions may differ across species implies that timber trade restrictions may affect the degree of heterogeneity of the forest resource. This may have important consequences for the logging pattern.

Reliable information about many of the key variables in our models is not readily available. Our price and cost data are based on direct communication with experts on tropical forestry. But since tropical forests vary greatly with respect to both the quality of the timber stands and the costs of logging, it is impossible to derive results with general validity from one single set of parameters. The simulations should therefore not be used to predict the effect of timber trade restrictions in any given area.

The price of tropical logs varies widely, from about 100 to over 800 USD/m<sup>3</sup>. The quality distribution is not uniform. Most species are worth less than 300 dollars. Logging and transport to log banks in the forest usually cost from 30 to 50 USD/m<sup>3</sup>. Cumulative costs at the saw mill, in the form of logs, may vary from 40 to 80 dollars, depending on transport costs and distances.

In the simulations, we let  $\bar{c}^1 = 40$ ,  $\bar{c}^2 = 80$  and  $r = 0.05$ . In none of our simulations is it optimal to log trees with a price less than 80 USD/m<sup>3</sup>. Hence, our results are valid for any quality distribution of species valued at less than 80 dollars. As for higher qualities, we shall assume a uniform quality distribution in the interval [80,280] USD/m<sup>3</sup>. Since species worth more than 280 dollars are rare, they will be ignored here.

The price function can now be written as a linear function  $p = y - xH$ , where the parameters  $y$  and  $x$  have replaced the general trade policy parameter  $\alpha$ . For reasons of numerical tractability, the capacity utilisation costs are assumed to be quadratic,  $c = b(\sum_i h^i)^2$ . The parameter values of  $x$  and  $b$  have been chosen in order to ensure that the optimal harvest pattern in the base case is empirically reasonable ( $b = 0.1$  and  $x = 0.16$  when logging is measured in 1,000 m<sup>3</sup>).<sup>8</sup>

The consequences of different kinds of changes in the price structure of the timber stand can now be studied by changing the values of  $y$  and  $x$ . We distinguish five different cases:

	<i>y</i> -value	<i>x</i> -value	Description <sup>9</sup>
Case 0	280	0.16	Base case
Case 1	252	0.144	Proportional price reduction for all qualities (10%)
Case 2	262	0.16	Equal absolute price reduction for all qualities (10% for AT)
Case 3	280	0.1888	Prices decline more for low qualities (10% for AT, no change on top)
Case 4 <sup>10</sup>	260	0.144	Relative price reduction is larger for high qualities than for low qualities

Simulation results are reported below. In the base case, the harvest volumes and the time consumption are reported in 1,000 m<sup>3</sup> and years, respectively. In the other cases, we report changes relative to base case.

<sup>8</sup>The logging pattern differs greatly between areas. In tropical America, it is common to harvest 10-20 m<sup>3</sup>/ha, while in Indonesia the harvest is usually 40 m<sup>3</sup> or more. If the total concession area is 50,000 ha, which is a relatively small concession by Indonesian standards, the optimal harvest in our base case is around 45 m<sup>3</sup>/ha. The time used to log the entire area is 14 years.

<sup>9</sup> An AT (*average tree*) is taken to be a tree worth 180 USD/m<sup>3</sup>.

<sup>10</sup> This price function will cross the base case price line from below at  $p = 80$ . But this is not a problem since the quality distribution for trees worth less than 80 USD can be chosen arbitrarily in all cases that we study.

Consider first the model without a binding time constraint. *Ceteris paribus*, lower prices will reduce marginal income and thus reduce optimal logging at any point of time (Eqs. (8)). The simulations show, however, that a lower price may lead to increased logging both in field 1 and in aggregate (Case 4). In order to explain these results, it is useful to take a closer look at the effect of price reductions on the optimal logging time.

*Sequential harvest - non-binding concession period*

	Case 0	Case 1	Case 2	Case 3	Case 4
$H_{T^1}^1$	1162.9	-2.7%	-7.3%	-13.6%	0.9%
$H_{T^1+T^2}^2$	1065.1	-5.2%	-9.0%	-14.2%	-0.8%
$H_{T^1}^1 + H_{T^1+T^2}^2$	2228.0	-3.9%	-8.1%	-13.9%	0.1%
$T^1$	4.38	7.3%	1.4%	-7.5%	6.6%
$T^2$	9.60	5.2%	0.0%	-7.6%	5.2%
$T^1 + T^2$	13.98	5.9%	0.4%	-7.6%	5.7%

*Sequential harvest – binding concession period ( $\bar{T} = 10$ )*

	Case 0	Case 1	Case 2	Case 3	Case 4
$H_T^1$	1145.3	-3.2%	-7.3%	-13.0%	0.3%
$H_{\bar{T}}^2$	1023.0	-6.7%	-9.1%	-12.7%	-2.3%
$H_T^1 + H_{\bar{T}}^2$	2168.3	-4.9%	-8.1%	-12.9%	-0.9%
$T$ (years)	4.09	4.6%	1.0%	-4.9%	4.2%

In field 1, reduced timber prices may affect the logging time through four different channels: 1) Lower timber prices reduce the profits earned in field 2. Hence, the cost of postponing the harvest in field 2 by spending more time in field 1 is reduced. This effect tends to *increase* the optimal  $T^1$  in all cases (Eq. (20)). 2) A lower value of  $y$  (cases 1, 2, and 4) reduces the marginal profit in field 1 at the terminal time. This can be compensated by logging in a larger area (i.e., increase  $a_{T^1}^1$ ). Such an upward shift in the area depletion rate tends to *reduce*  $T^1$  (Eq. (20)). 3) Changes in the value of  $x$  also affect the marginal profit at the terminal time, but in the opposite direction of  $y$ . Hence, a lower  $x$  tends to *increase*  $T^1$  in cases 1 and 4, and a higher  $x$  tends to *reduce*  $T^1$  in case 3. 4) Changes in the value of  $x$  affect  $\dot{a}$ , i.e., the slope of the area depletion curve. A higher value of  $x$  tends to make  $\dot{a}$  more negative. The intuition is that an increase in  $x$  effectively makes the forest resource more heterogeneous. This will



increase the profitability of tilting the harvest of high qualities towards the present by starting the harvest in each field with a relatively high area depletion rate. For a given value of  $a_{T^1}^1$ , an increase in  $x$  thus tends to *reduce*  $T^1$ . This is what happens in case 3. In cases 1 and 4, a less heterogeneous forest tends to *increase*  $T^1$ .

*The effects of reduced timber prices on the optimal logging time in field 1 ( $T^1$ ).*

	1) Effect through reduced $\pi^{2*}$	2) Direct effect of change in $y$	3) Direct effect of change in $x$	4) Effect of change in $x$ through $\dot{a}$
Case 1	+	-	+	+
Case 2	+	-	0	0
Case 3	+	0	-	-
Case 4	+	-	+	+

When it becomes optimal to stay longer in field 1, the harvest in field 1 tends to increase, thus counteracting the general tendency to reduce harvests in all fields. The increase in  $T^1$  is large in both case 1 and case 4, but it is only in the latter case that the counteracting effect dominates. The essential difference between cases 1 and 4 is that in case 4, the price reduction on the marginal species in field 1 is very small, implying that for a given  $T^1$ , the incentive to reduce logging is not very strong. Therefore, the increase in logging that comes about through higher  $T^1$  is the dominating effect.

In field 2, the terminal condition is simpler than in field 1; it is only the fourth effect above that is relevant for the optimal  $T^2$ . This is confirmed by the simulation results. Furthermore, we observe that the harvest in field 2 is reduced in all cases. However, the reduction is very small in case 4, because the price reduction is very small for marginal trees, and because the forest has become more homogeneous, making it optimal not to rush through the field as fast as before.

It is quite surprising that timber trade restrictions may increase total logging (case 4). The result is due to the constraints that the sequential harvest procedure imposes upon the logging pattern. What drives the marginal profit to zero (in all fields except the last one in the sequence) is not a low level of profit in the fields as such, but the costs of postponing the harvest in subsequent fields. Since trade restrictions reduce these costs, total logging may

increase. This result is, however, not very robust to changes in the parameters of the model, and its practical relevance is therefore probably limited.

Consider next the model with a binding time constraint. Obviously, since the total logging time is now fixed, it is less likely that timber trade restrictions will increase total logging. The simulations confirm that total logging will indeed be reduced. But logging is not necessarily reduced in all fields; in case 4, logging increases in field 1. Just as in the model above, this increase in logging comes about because it is optimal to stay longer in field 1. But since more logging time in field 1 directly reduces the time available in field 2 in this model, the harvest in field 2 is more sharply reduced than in the model with a non-binding time constraint. Total logging is therefore reduced.

The intuition for these results is that in addition to the general tendency to reduce logging, there may be some reallocation of the logging effort between the fields. Whether effort is reallocated from high cost to low cost fields (or vice versa) depends on how the trade restrictions affect the price of the marginal tree harvested at time  $T$  in the respective fields. The first order condition for the optimal switching date (Eq. (14)) shows that if there are cost differences between the fields ( $\bar{c}^1 < \bar{c}^2$ ), the price of the marginal tree in field 1 at the switching date will be lower than the price of the marginal tree in field 2 (i.e.,  $p(h_T^{1*}/a_T^{1*}) < p(h_T^{2*}/a_T^{2*})$ ). Therefore, if the price reduction is larger for high qualities than for low qualities, it will typically be optimal to stay longer and harvest more low quality trees in field 1 before switching to field 2. The time available in field 2 is correspondingly reduced. Hence, the logging effort is in fact reallocated between the fields. This mechanism is operating in both case 1 and case 4 in the simulations. The opposite effect (i.e., reallocation of logging from field 1 to field 2) is operating in case 3, but it is not strong enough to dominate over other effects in our simulations. However, with a sufficiently convex capacity cost function, the price change in case 3 would lead to increased harvest in field 2 and reduced harvest in field 1 (see Proposition A.1 in the Appendix).

In a paper by von Amsberg (1998) it is emphasised that timber trade restrictions will lead to an increase in the number of untouched fields. Despite important differences between the models, a similar result is obtained here. It is easily seen that if the price of the most valuable tree falls below  $\bar{c}^2$ , field 2 will never be opened. In the model with a binding time constraint, field 2 might be left untouched even if  $p(0, \alpha) > \bar{c}^2$ , because it may then be more profitable at any time to log marginal trees in field 1 rather than the most valuable trees in field 2. Moreover, by taking into account that there may be fixed costs related to making new fields accessible, the price reduction needed to leave field 2 untouched would be even smaller.

Von Amsberg also argues that lower timber prices will lead to more untouched forest at *any point of time* during the harvest period. Our analysis shows that this result is not generally valid in a model with heterogeneous tree quality; if the price reduction is larger for low qualities than for high qualities (case 3), it is typically optimal to switch from field 1 to field 2 at an earlier date. In other words, it is optimal to proceed faster through the forest.

### 3.2 Simultaneous harvest

With simultaneous harvest, the logging companies have the opportunity to log in several fields at the same time. Discounting implies that it is optimal to harvest trees with a high price-cost margin first. Since tree qualities vary within each field, it is then optimal to shift the logging effort back and forth among fields.

With simultaneous harvest, the income at time  $t$  is given by  $R_t^i = \sum_i \int_{H_t^{i-}}^{H_t^{i+}} p(h, \alpha) dh$ , where  $H_t^{i-}$  and  $H_t^{i+}$  are the aggregate number of harvested trees in field  $i$  at time  $t^-$  and  $t^+$ . By inserting this income function into the general profit function (Eq. (1)), it is straightforward to show that the optimal logging pattern in a two field model is defined by the condition

$$p(H_t^i, \alpha) - \bar{c}^i - c'(h_t^1 + h_t^2) \leq 0, \quad i = 1, 2, \quad (21)$$

in addition to the usual non-negativity constraints and the conditions of complementary slackness. At each point of time, the marginal profit from increasing the harvest should be non-positive – and equal to zero whenever  $h_t^i > 0$ . At the beginning of the concession period, it is

optimal to log in the low cost field only. Field 2 is opened at time  $T$ , defined by  $p(0, \alpha) - p(H_T^1, \alpha) = \bar{c}^2 - \bar{c}^1$ , i.e., when the price difference between the most valuable tree in field 2 and the marginal tree in field 1 equals the difference between the field-specific harvest costs. After that, the two fields are logged simultaneously according to the following rule

$$p(H_t^2, \alpha) - p(H_t^1, \alpha) = \bar{c}^2 - \bar{c}^1, \quad \forall t > T. \quad (22)$$

At each point of time, the difference between the prices of the marginal trees in the respective fields should equal the difference between marginal harvest costs.

### 3.2.1 Timber trade restrictions

Eq. (21) clearly implies that reduced timber prices will lead to reduced total logging at any level of  $H^i$ , and therefore to reduced total logging as long as the time constraint is binding. But as in the sequential model, there may be reallocation of logging efforts between the fields, possibly leading to increased harvest in certain fields. The effect of reduced timber prices on the harvest pattern can be studied by differentiating Eq. (22) with respect to  $\alpha$ ,

$$p_\alpha(H_t^2, \alpha) - p_\alpha(H_t^1, \alpha) + p_H(H_t^2, \alpha) dH_t^2 / d\alpha - p_H(H_t^1, \alpha) dH_t^1 / d\alpha = 0. \quad (23)$$

It is impossible to derive unambiguous results without making further assumptions about the price function. In the following, we use a linear price function, implying that  $p_H$  is a constant. We start by studying the effect of an equal absolute price reduction (cf. case 2 above). Then,  $p_\alpha$  is a constant, and Eq. (23) can be written as  $p_H(dH_t^2 / d\alpha - dH_t^1 / d\alpha) = 0, \forall t > T$ . Hence, the absolute change in the harvest must be identical in the two fields at any point of time after  $T$ . Moreover, it is easy to show that the aggregate harvest in field 1 at time  $T$  ( $H_T^1$ ) will not be affected by a price reduction of this kind. Since total logging must fall, it then follows that logging is reduced in both fields when the price reduction is identical for all species.

If timber prices are reduced more for high qualities than for low qualities, then  $p_\alpha(H_t^2, \alpha) > p_\alpha(H_t^1, \alpha)$ , because the quality of the marginal tree is higher in field 2 at any point of time. Eq. (23) then implies that  $p_H(dH_t^2 / d\alpha - dH_t^1 / d\alpha) < 0$ , and  $dH_t^2 / d\alpha > dH_t^1 / d\alpha$ . In

other words, lower timber prices will have a less negative impact on the logging volume in field 1 than in field 2. Hence, there will be some reallocation of logging effort from field 2 to field 1. In fact, this reallocation effect may be so strong that the logging volume increases in field 1. Whether this will in fact happen, depends on the shape of the capacity cost function and the length of the concession period. One extreme is to assume a fixed logging capacity per unit of time. Timber price reductions will then not affect total logging as long as the concession period is binding, i.e.,  $dH_t^2/d\alpha + dH_t^1/d\alpha = 0$ . But since  $dH_t^2/d\alpha > dH_t^1/d\alpha$ , this must imply that  $dH_t^1/d\alpha > 0$ ; logging increases in field 1 as long as the time constraint binds.

Logging may surely increase in field 1 with a more "soft" capacity constraint as well, but then the constraint imposed by the length of the concession period must bind to a greater extent. The following simulations illustrate this point. The numerical values are the same as in section 3.1.3, except that the concession period is much shorter ( $\bar{T} = 1$ ).

*Simultaneous harvest*

	<i>Base case</i> $y = 280, x = 0.16$	<i>Uniform price reduction</i> $y = 270, x = 0.16$	<i>Larger price reduction for high qualities<sup>11</sup></i> $y = 270, x = 0.144$	<i>Larger price reduction for low qualities</i> $y = 280, x = 0.17$
$H_{\bar{T}}^1$	582.1	561.7	584.4	569.2
$H_{\bar{T}}^2$	332.1	311.7	306.6	333.9
$H_{\bar{T}}^1 + H_{\bar{T}}^2$	914.3	873.4	891.0	903.1
$T$	0.23	0.24	0.27	0.21

With a uniform price reduction across qualities, logging is reduced in both fields. There is no reallocation of logging efforts between the fields. When prices decline more for high qualities than for low qualities, logging effort is reallocated to the low cost field. Although total logging is reduced, the harvest in field 1 increases. In order to obtain such a result, it is essential that it is optimal to postpone the opening of field 2 quite considerably. Note that as long as only field 1 is logged, the harvest rate in field 1 is much higher than when logging takes place in both fields simultaneously. Even though lower timber prices lead to reduced harvest at any point of

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<sup>11</sup> This price function crosses the base case price function from below at the harvest level 625,000 m<sup>3</sup>. But since the optimal harvest is always smaller than this amount, we can be sure that prices are indeed reduced for all relevant qualities.

time, logging may therefore increase in field 1 if it becomes profitable to use more of the concession time in field 1 alone, i.e., if  $T$  increases. A sharper price reduction for high qualities than for low qualities makes the most profitable tree in field 2 less valuable relative to marginal trees in field 1 and thus gives an incentive to harvest more in field 1 before field 2 is opened.

Conversely, a larger price reduction for low qualities than for high qualities tends to reduce the optimal  $T$  and thus increase the logging time in field 2. *Ceteris paribus*, this leads to more logging in field 2. The simulations show that this effect may more than outweigh the general tendency to reduce logging due to lower prices, implying that logging in field 2 may increase.

The most important effects of timber trade restrictions on logging behaviour are summarised in

**PROPOSITION 1:** *Lower timber prices tend to reduce logging and reduce the pressure on virgin forests. But logging may increase in low cost (high cost) fields if prices decline more (less) on high quality timber than on low quality timber. Although total logging is reduced in most cases, total logging may increase if the forest is logged sequentially, the concession period is non-binding, and prices are reduced most on high quality timber.*

#### **4. Timber trade restrictions and the use of land**

The most forceful objection against trade restrictions on tropical timber and timber products has been that by making forestry less profitable, such measures will promote the conversion of forest land into agricultural uses (e.g., Vincent (1990), Grainger (1993), ITTO (1993), von Amsberg (1998). The following analysis questions the general validity of this claim.

Small-scale shifting cultivators conduct a major share of agricultural conversion in the tropics. Such conversion is often "unplanned" in the sense that it is not a result of a deliberate choice by the forest owner, who usually is the central government. In addition, some agricultural conversion is the result of government decisions to reallocate forestland to agricultural purposes. Both these cases of agricultural conversion are discussed below.

#### *4.1 Planned agricultural conversion*

Planned conversion of forestland to alternative purposes takes place after balancing the value of the forest against the value of relevant alternatives. There is no doubt that lower timber prices reduce the profitability of forestry, which implies that the alternative cost of converting *the entire forest area* into alternative uses is reduced. In practice, however, it is rarely an interesting option to convert the entire tropical forest into agricultural land. The quality of the soil is typically very poor in areas covered by tropical forest. Moreover, steeply sloped forests hills are often unsuitable for agriculture due to the risk of soil erosion. A more relevant question, therefore, is to ask how timber trade restrictions affect the incentives for a *marginal* expansion of the agricultural area. As will be demonstrated shortly, timber trade restrictions may in some cases weaken the incentives for a marginal expansion of agricultural land.

In the following, a marginal expansion of agricultural land shall mean that one logging field (field 1) is converted to agriculture. (Field 1 is chosen because the most profitable logging field is assumed to be most attractive for agriculture as well, e.g. due to low transportation costs.) Timber trade restrictions will strengthen the incentives for a marginal agricultural expansion if they reduce the costs of converting field 1 to agriculture. The conversion costs are the sum of the direct clearing costs (*DCC*) and the alternative value of the field as forestland (*AVF*).

Consider first the effect of timber trade restrictions on *DCC*. Trade restrictions will affect *DCC* insofar as the field is logged before conversion to agriculture. When fewer trees are logged, clearing for agriculture becomes more difficult and thus more costly. Timber trade restrictions, by tending to reduce the total harvest, thus tend to increase *DCC* and discourage agricultural conversion. Note, however, that *DCC* may be reduced in field 1 if the price of high value timber declines more than the price of low value timber, due to reallocation of logging effort towards field 1.

The value of the trees logged prior to conversion can be treated as a discount in *DCC*. Lower timber prices reduce the value of this discount and thus increase net clearing costs. We conclude that there will be an unambiguous increase in *DCC*, implying a weakening of the

incentives for agricultural expansion, as long as timber prices do not decline more for high qualities than for low qualities.

Consider next the effect of timber trade restrictions on the alternative value of field 1 as forestland (*AVF*). In this paper, we have devoted our attention to the optimal depletion of virgin or old-growth forest. The returns to old-growth logging are however largely irrelevant to the post-logging land use decision. Indeed, this decision hinges on the relative profitability of agriculture and second-growth forest. Although logging companies with short concessions are likely to pay little attention to such secondary growth, it may play a more important role for the land use decisions of the central government.

Let  $\pi_{-1}^{is}(\alpha, t)$  and  $\pi_0^{is}(\alpha, t)$  denote the profit from secondary forestry in field  $i$  at time  $t$  when field 1 is, respectively is *not*, converted to agriculture after the initial logging of the old-growth forest. If the conversion of field 1 does not affect profits earned in other fields, the alternative value of field 1 is simply the present value of future profit in this field, i.e.,  $AVF = \int_0^{\infty} e^{-rt} \pi_0^{is}(\alpha, t) dt$ . Reduced logging in field 1 may however increase the profits earned in other fields. This happens, for instance, when the costs of logging depend on the total harvest per period. In Section 3, it was argued that in order to achieve a realistic time path of logging in our model, we had to assume that marginal logging costs are increasing in the aggregate harvest per period. In that case, the conversion of one field to agriculture implies that the profitability of logging will increase in remaining fields. This represents a reduction in the net costs of a partial conversion of forestland into agricultural land and will in the following be called the *benefit of capacity release*. This effect has not previously been discussed in the literature, since loggers have been assumed to possess unlimited logging capacity at constant marginal logging costs. Taking into account the potential benefit of capacity release leads to the following general expression for the alternative value of field 1:

$$AVF = \int_0^{\infty} e^{-rt} \sum_i [\pi_0^{is}(\alpha, t) - \pi_{-1}^{is}(\alpha, t)] dt. \quad (24)$$

It is beyond the scope of this paper to go into details about the management of secondary forests. Therefore, we abstract from the questions of optimal rotation and optimal effort and



simply assume that there is natural regrowth and that the forest delivers a given timber crop with regular time intervals. In order to determine the effect of timber trade restrictions on  $AVF$  it thus suffices to study the effect on the profits from only one of the future rotations. Let  $\hat{\pi}$  denote the reduction in profits from any future rotation due to the conversion of field 1 to agriculture, i.e.,  $\hat{\pi} \equiv \sum_i [\pi_0^{is}(\alpha) - \pi_{-1}^{is}(\alpha)]$ . Timber trade restrictions reduce (increase)  $AVF$  and thus promote (prevent) the expansion of agricultural land if  $d\hat{\pi}/d\alpha > 0$  ( $< 0$ ).

It is not trivial to characterise profits earned in field  $i$  in a model with capacity utilisation costs, because these costs are a function of the total harvest in each *period* and therefore not field specific. In order to circumvent this problem and still retain a model with potential benefits of capacity release, we shall assume constant marginal logging costs and a fixed, but possibly non-binding, capacity constraint.<sup>12</sup> By abstracting from the issue of discounting, profits earned in field  $i$  can then be written as:

$$\pi^i = \int_0^{H^i} \tilde{p}(h, \alpha) dh - \bar{c}^i H^i, \quad (25)$$

where  $\tilde{p}(H, \alpha)$  is the unit price of the  $H$ th most valuable tree in the secondary forest and  $H^i$  is the total harvest in the field at each rotation. The effect of timber trade restrictions on  $\hat{\pi}$  can now be written

$$\frac{d\hat{\pi}}{d\alpha} = \sum_i \left[ \int_0^{H_0^i} \frac{\partial \tilde{p}(h, \alpha)}{\partial \alpha} dh + (\tilde{p}(H_0^i, \alpha) - \bar{c}^i) \frac{dH_0^i}{d\alpha} - \int_0^{H_{-1}^i} \frac{\partial \tilde{p}(h, \alpha)}{\partial \alpha} dh - (\tilde{p}(H_{-1}^i, \alpha) - \bar{c}^i) \frac{dH_{-1}^i}{d\alpha} \right]. \quad (26)$$

**PROPOSITION 2:** *If the capacity constraint does not bind, timber trade restrictions will reduce  $AVF$ , which increases the profitability of a marginal expansion of agricultural land.*

*Proof:* When the capacity constraint does not bind,  $\tilde{p}(H^i, \alpha) - \bar{c}^i = 0$ ,  $\forall i$ . Therefore,  $H_0^i = H_{-1}^i$ ,  $\forall i \neq 1$ . Then, since  $H_{-1}^1 = 0$ ,  $d\hat{\pi}/d\alpha = \int_0^{H_0^1} \frac{\partial \tilde{p}(h, \alpha)}{\partial \alpha} dh > 0$ .

<sup>12</sup> To postulate a fixed capacity limit is equivalent to assuming that the capacity cost function is infinitely convex at a particular harvest volume.

When the capacity constraint does not bind, the marginal profit is zero in all fields. Therefore, the conversion of one field to agriculture has no effect on the harvest in the remaining fields. The cost of converting field 1 to agriculture is therefore equal to the foregone profit from timber extraction in field 1. Since lower timber prices cause an unambiguous reduction in profits in all fields where the marginal profit is zero,  $AVF$  is bound to decline.

However, this result does not in general carry over to the case with a binding capacity constraint. If the capacity constraint binds, the logging capacity that is released when field 1 is converted to agriculture, will be utilised in the remaining fields. This reduces the net costs of agricultural expansion. When timber prices are reduced, the benefit of capacity release is diminished. This tends to prevent the conversion of forests to agricultural use. If the decline in the benefit of capacity release is greater than the profit reduction in field 1, the incentives for a marginal agricultural expansion are weakened by timber trade restrictions. Whether this will in fact happen depends on 1) how the trade restrictions affect the price structure of timber and 2) the number of fields.

It is easy to show that if there is a fixed, binding capacity constraint and timber trade restrictions cause the same absolute price reduction for all tree qualities (cf. case 2 above), the incentives for a marginal agricultural expansion remain unchanged. When prices are reduced by the same amount for all species, the decline in the benefit of capacity release is equal to the magnitude of the price reduction times the released capacity. Obviously, this is identical to the reduction in profits that timber trade restrictions cause in field 1, which is the source of the released capacity. Hence, the two effects cancel out and leave the incentives for agricultural expansion unchanged (see Proposition A.4 in the Appendix).

The assumption about a fixed capacity constraint is not very realistic. If instead we impose a less convex capacity utilisation cost, reduced logging in field 1 will not be fully replaced by increased logging in remaining fields. Normally, therefore, an equal price reduction for all tree qualities will imply a reduction in  $AVF$  and thus a strengthening of the incentives for a marginal agricultural expansion.

It is also easy to show that if prices are reduced more for low quality than for high quality timber (cf. case 3 above),  $AVF$  may increase. Consider an example with two identical logging fields, but where agriculture yields positive profit in field 1 only. Assume that there is a fixed capacity constraint, and that the capacity that is released if field 1 is converted to agriculture will be utilised in field 2. Since the optimal harvest is identical in both fields at the outset, released capacity will be used to harvest trees of lower quality. Then, if the price reduction on these low quality trees is larger than the price reduction on high quality trees, the profit loss in field 1 due to lower timber prices will be outweighed by an even greater decline in the benefit of capacity release. Hence,  $AVF$  will increase. It is trivial that this result may hold even if reduced logging in field 1 is not fully replaced by increased logging in field 2, as will be the case with a less convex capacity cost function. The result will clearly also be valid with a small difference between the marginal logging costs. But if the fields are very heterogeneous,  $AVF$  may decrease. The reason is that the quality of a marginal tree in field 2 will then be relatively high, implying that the benefit of capacity release is reduced less with this kind of price reduction.

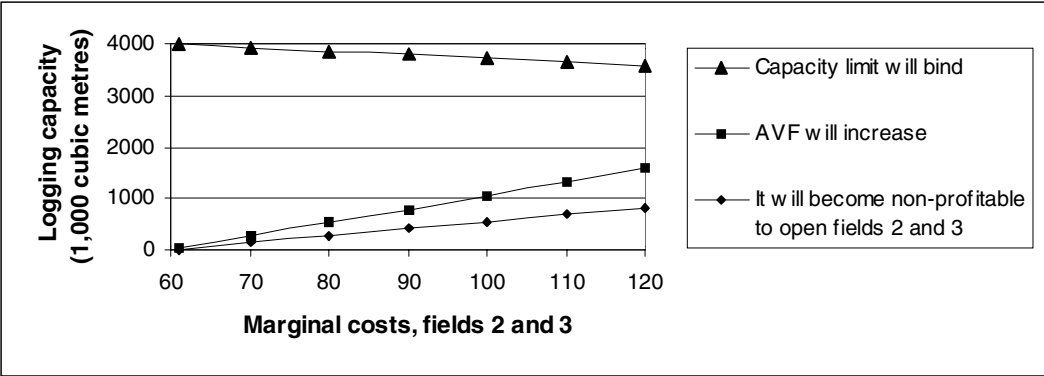
Note that since only high quality trees are logged in marginal fields, the inducing of a greater price decline for low quality trees than for high quality trees is a strategy that is less likely to reduce the pressure on virgin forests than if prices are reduced most for high qualities. Does this imply that there is a trade-off between protection of virgin forests and the desire to avoid agricultural expansion? Certainly, that may be the case. If the example that was just given had been extended to include a third field with higher marginal harvest costs than the other fields, then the timber trade restrictions which keep up the price of high qualities while lowering the price of low qualities, might induce the loggers to open the third field. The reason is that the marginal profit in the third field is kept up while marginal profit declines in the fields where logging is already taking place.

In von Amsberg (1998), the trade-off between protection of virgin forest and avoidance of agricultural expansion seems inevitable. That is not the case here, though. In particular, if there

are more than two logging fields, both aims may be attained by using trade provisions that cause a greater reduction in the price of high quality trees than in the price of low quality trees.

**PROPOSITION 3:** *When loggers are capacity constrained, timber trade restrictions may both increase AVF, which reduces the profitability of a marginal agricultural expansion, and promote the protection of the virgin forest.*

*Proof:* The proposition will be proved by simulation. Assume that there are two high cost fields and one low cost field. The quality distribution in each field is the same as in section 3. We impose a 10% price reduction on all qualities. We then calculate the level of the logging capacity below which (1) the capacity limit is binding, (2) AVF will increase, and (3) AVF will increase and the two high cost fields remain untouched due to the price fall on timber. Calculations are performed for different degrees of heterogeneity between the fields; while the average of  $\bar{c}^1$  and  $\bar{c}^2(=\bar{c}^3)$  is 60 USD in all cases, we let the difference between  $\bar{c}^2(=\bar{c}^3)$  and  $\bar{c}^1$  vary between 0 and 120. The results are reported in the diagram below. If marginal



logging costs differ between fields and the logging capacity is sufficiently low, timber trade restrictions lead to both an increase in AVF and to less intrusion into the virgin forest. The reason why we obtain these results, even when timber prices are reduced more for high qualities than for low qualities, is that the released capacity is utilised in more than one logging field. When the released capacity is used in a greater number of fields, the average quality for trees harvested by released capacity will increase. Therefore, timber trade restrictions that induce large price reductions for high quality timber will reduce the benefit of capacity release more significantly, thus weakening the incentives for agricultural expansion. The simulations suggest, however, that quite restrictive capacity limits are needed in order to get this result.

The underlying reason why timber trade restrictions may increase  $AVF$  is that the activity level in field 1 affects the profits from other fields as well, either because marginal logging costs increase with total logging (capacity utilisation costs) or because there is a fixed capacity constraint. The considerable extent of "high-grading" that takes place in tropical forests (see e.g., ITTO (1993)) may indicate that such capacity constraints are real; the fact that loggers discard trees of significant value in order to harvest even more valuable trees in other places, suggests that the loggers may be capacity constrained.

A theoretical argument that explains why binding capacity constraints may arise in optimum is that the threat about future trade restrictions may make loggers reluctant to invest in sufficient capacity. For certain beliefs about future timber prices, the capacity levels which yield the results of Proposition 3 might therefore be *ex ante* optimal. Similarly, uncertainty created by insecure concessions may lead rational loggers not to invest in sufficient capacity.

#### 4.2 "Unplanned" agricultural conversion

"Unplanned" agricultural conversion is conducted by small-scale shifting cultivators. These farmers rarely utilise the timber stands commercially. Reduced timber prices will therefore not have any direct effect on their activities. Their behaviour might be affected indirectly, though, through changes in the harvest pattern of logging companies.

A major constraint on the expansion of shifting cultivation is accessibility; a tropical forest do often not become accessible until it has been opened up by roads provided by, for example, logging companies. Grainger (1993) and others argue that agricultural expansion following the logging frontier has been one of the main vehicles of deforestation in Asia. The analysis in Section 3 showed that, for a given allocation of land, timber trade restrictions would tend to increase the number of untouched fields. When fewer fields are opened up, the forest becomes less accessible for agricultural expansion than it otherwise would be, leading to increased clearing costs and less agricultural conversion by shifting cultivators. However, there is also a possibility that reduced timber prices will lead to conversion of forest land to other purposes. In that case, released logging capacity may be utilised in fields that previously were untouched.

That would ease the access of shifting cultivators and might contribute to more unplanned agricultural conversion.

Clearing costs are also affected by the number of trees removed by the loggers. When fewer trees are logged, clearing becomes more difficult and thus more costly. If timber prices are reduced uniformly across qualities, logging tends to decline in all fields. In that case, timber trade restrictions increase the clearing costs of shifting cultivators and thus contribute to less "unplanned" agricultural conversion.

## **5. Concluding remarks**

This study has pointed out factors that are of crucial importance for the effect of timber trade restrictions on tropical deforestation. By taking account of the heterogeneity of the tropical forest resource – including both differences in tree qualities and differences in marginal logging costs across fields – it has been shown that the effects of timber trade restrictions on the logging pattern and on the profitability of agricultural expansion depend critically on 1) how trade restrictions affect the price structure across different tree qualities, 2) whether or not marginal logging costs differ across fields, 3) technological factors; such as the harvest procedure and the existence of capacity constraints, and 4) whether or not the duration of the awarded concession is a binding constraint.

Among the more constructive results of the paper is that in order to reduce logging in all fields, one should aim at a relatively uniform price reduction across tree qualities. A uniform price reduction is however likely to increase the profitability of agricultural expansion. In order to reduce the probability of agricultural expansion in the wake of timber trade restrictions, either a relatively large price reduction on low qualities or a relatively large price reduction on high qualities might be appropriate, depending on the local circumstances. These results suggest that quite fine-tuned policy instruments may be needed in order to avoid undesirable effects of reduced timber prices. It may seem unlikely that such fine-tuning possibly can be achieved through trade restrictions on tropical timber and timber products, but that question is still open to debate.

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## Appendix

This Appendix uses a simplified version of the logging models developed earlier in this paper in order to obtain some analytical results about the consequences of timber trade restrictions. The simplification is that logging capacity per period is assumed fixed and normalised to 1.

We shall constrain our attention to three particular ways in which trade restrictions may affect timber prices, represented by the following functional forms:

<p><i>Case I:</i> <math>p(H, \alpha) = \alpha \hat{p}(H)</math></p>	<p><i>Proportional price reduction</i></p>
<p><i>Case II:</i> <math>p(H, \alpha) = \alpha + \hat{p}(H)</math></p>	<p><i>Equal absolute price reduction</i></p>
<p><i>Case III:</i> <math>p(H, \alpha) = \hat{p}(0) - \frac{1}{\alpha}(\hat{p}(0) - \hat{p}(H))</math></p>	<p><i>The price reduction is larger for low qualities</i></p>

### A.1 The concession period - a binding constraint

**PROPOSITION A.1:** *If the logging capacity is fixed and the concession period is binding, timber trade restrictions will lead to 1) reduced (increased) logging in the high cost field and increased (reduced) logging in the low cost field if the prices decline as in case I (case III), i.e., if the price of high quality timber declines more (less) than the price of low quality timber, 2) no change in the logging pattern if the price reduction is the same for all tree qualities (case II) and/or  $\bar{c}^1 = \bar{c}^2$ , and 3) an increase (or no change) in the number of untouched logging fields.*

*Proof:* It is trivial that the capacity ceiling on the harvest in each period will bind. Hence,  $h_t = 1$ . Eq. (14) then simplifies to

$$p(1/a_T^{1*}, \alpha) - \bar{c}^1 = p(1/a_T^{2*}, \alpha) - \bar{c}^2. \quad (\text{A.1})$$

Differentiation with respect to  $\alpha$  yields

$$\frac{dT}{d\alpha} = -\frac{1}{D} \left[ p_\alpha \left( \frac{1}{a_T^{1*}}, \alpha \right) - p_\alpha \left( \frac{1}{a_T^{2*}}, \alpha \right) + p_H \left( \frac{1}{a_T^{1*}}, \alpha \right) \left( \frac{-1}{(a_T^{1*})^2} \right) \frac{\partial a_T^{1*}}{\partial \alpha} - p_H \left( \frac{1}{a_T^{2*}}, \alpha \right) \left( \frac{-1}{(a_T^{2*})^2} \right) \frac{\partial a_T^{2*}}{\partial \alpha} \right],$$

where  $D \equiv p_H(-1/(a_T^{1*})^2)\partial a_T^{1*}/\partial T - p_H(-1/(a_T^{2*})^2)\partial a_T^{2*}/\partial T < 0$ . In order to proceed, we need the following

**LEMMA:** For each of the price functions (I), (II), and (III),  $\frac{\partial \dot{a}_t^i}{\partial \alpha} = \frac{\partial a_t^i}{\partial \alpha} = 0$ .

*Proof:* Eqs. (9) show that  $\dot{a} = rR_a/R_{aa}$  when  $h_t = 1$ . Hence,

$$\frac{\partial \dot{a}}{\partial \alpha} = r \frac{(R_{a\alpha} + R_{aa} \partial a / \partial \alpha)R_{aa} - R_a(R_{aaa} + R_{aaa} \partial a / \partial \alpha)}{(R_{aa})^2}.$$

Since the whole field area will be logged ( $A_T = 1$ ), it is the case that  $\partial \dot{a} / \partial \alpha = 0 \Rightarrow \partial a / \partial \alpha = 0$ .

In order to prove the lemma it therefore suffices to prove that  $R_{aa}R_{a\alpha} = R_aR_{aaa}$ . It can easily be checked that this equation is satisfied for each of the price functions (I), (II), and (III).

Thus, with any of the price functions (I)-(III),  $\frac{dT}{d\alpha} = -\frac{1}{D} \left[ p_\alpha \left( \frac{1}{a_T^{1*}}, \alpha \right) - p_\alpha \left( \frac{1}{a_T^{2*}}, \alpha \right) \right]$ . Using

this expression in combination with Eq. (A.1) proves the first and the second statement of the proposition. The third statement is easily proved by realising that if the price reduction is so large that  $p(0, \alpha) < \bar{c}^2$ , field 2 will not be opened. Note, however, that with price function (III), the price of the most valuable tree ( $p(0, \alpha)$ ) will not be affected at all by trade restrictions. Trade restrictions will then not affect the number of untouched fields in our model. However, by including some fixed costs related to the opening of fields, a greater number of untouched fields would be possible even with price function (III). •

## A.2 The concession period - a non-binding constraint

With a fixed capacity constraint, Eq. (17) simplifies to

$$p(1/a_{T^2}^{2*}, \alpha) - \bar{c}^2 = 0. \quad (\text{A.2})$$

The optimal time used in field 1 is now given by

$$p(1/a_{T^1}^{1*}, \alpha) - \bar{c}^1 = r\pi^{2*}(\alpha). \quad (\text{A.3})$$

**PROPOSITION A.2:** *If the logging capacity is fixed and the concession period is non-binding, timber trade restrictions will lead to 1) reduced logging in the last field in the sequence, 2) reduced or increased logging in the first field in the sequence, 3) reduced or increased total logging, 4) reduced logging in all fields if the price reduction is the same for all tree qualities, and 5) an increase (or no change) in the number of untouched logging fields.*

*Proof:* Implicit differentiation of Eq. (A.2) yields

$$\frac{dT_2}{d\alpha} = -\frac{p_\alpha(1/a_{T_2}^{2*}, \alpha)}{p_H(-1/(a_{T_2}^{2*})^2)\partial a_{T_2}^{2*}/\partial T_2} > 0, \quad (\text{A.4})$$

which proves the first statement of the proposition. Implicit differentiation of Eq. (A.3) yields

$$\frac{dT_1}{d\alpha} = -\frac{p_\alpha(1/a_{T_1}^{1*}, \alpha) - r\pi_\alpha^{2*}}{p_H(-1/(a_{T_1}^{1*})^2)\partial a_{T_1}^{1*}/\partial T_1}. \quad (\text{A.5})$$

The sign of  $dT_1/d\alpha$  is ambiguous.  $dT_1/d\alpha$  is positive if the rate of interest is close to zero. Numerical simulations in Section 3.1.3 showed that lower timber prices may lead to increased logging in field 1 ( $dT_1/d\alpha < 0$ ), and that this increase may be larger than the logging reduction in field 2.

When all timber prices are reduced with the same amount,  $p_\alpha = k$  for all qualities. Hence,

$$\begin{aligned} \frac{dT_1}{d\alpha} &= -\frac{k - r \int_0^{T_2} \left[ a_i^{2*} \int_0^{a_i^{2*}} k dh \right] e^{-rt} dt}{p_H(-1/(a_{T_1}^{1*})^2)\partial a_{T_1}^{1*}/\partial T_1} = -\frac{k - r \int_0^{T_2} k e^{-rt} dt}{p_H(-1/(a_{T_1}^{1*})^2)\partial a_{T_1}^{1*}/\partial T_1} \\ &= -\frac{k - rk \left( \frac{1}{r} - \frac{1}{r} e^{-rT_2} \right)}{p_H(-1/(a_{T_1}^{1*})^2)\partial a_{T_1}^{1*}/\partial T_1} = -\frac{ke^{-rT_2}}{p_H(-1/(a_{T_1}^{1*})^2)\partial a_{T_1}^{1*}/\partial T_1} > 0. \end{aligned} \quad (\text{A.6})$$

The last statement of the proposition follows from the same type of argument as was used in the proof of Proposition A.1. •

### A.3 Simultaneous harvest

**PROPOSITION A.3:** *With simultaneous harvest and a fixed logging capacity, timber trade restrictions will lead to 1) reduced (increased) logging in the high cost field and increased (reduced) logging in the low cost field at each point of time if prices are reduced as in case I (case III), i.e., if the price of high quality timber declines more (less) than the price of low quality timber, 2) no reallocation of logging between fields if the price reduction is the same for all qualities (case II), and 3) an increase (or no change) in the number of untouched logging fields.*

*Proof:* The last statement follows from the same logic as was used in the proof of Proposition A.1. In order to prove statements 1 and 2, differentiate Eq. (22) with respect to  $\alpha$ , taking into account that with a fixed logging capacity  $dH_t^1/d\alpha + dH_t^2/d\alpha = 0$ :

$$p_\alpha(H_t^2, \alpha) - p_\alpha(H_t^1, \alpha) - [p_H(H_t^2, \alpha) + p_H(H_t^1, \alpha)]dH_t^1/d\alpha = 0. \quad (\text{A.7})$$

Since  $p_H < 0$ , it follows that

$$\begin{aligned} p_\alpha(H_t^2) > p_\alpha(H_t^1) &\Rightarrow dH_t^1/d\alpha < 0 \text{ and } dH_t^2/d\alpha > 0, \\ p_\alpha(H_t^2) = p_\alpha(H_t^1) &\Rightarrow dH_t^1/d\alpha = dH_t^2/d\alpha = 0, \\ p_\alpha(H_t^2) < p_\alpha(H_t^1) &\Rightarrow dH_t^1/d\alpha > 0 \text{ and } dH_t^2/d\alpha < 0. \end{aligned} \quad (\text{A.8})$$

The proof is completed by realising that the marginal tree in the high cost field always is of higher quality than the marginal tree in the low cost field (i.e.,  $H_t^1 > H_t^2$ ).•

### A.4 Timber trade restrictions and the use of land

**PROPOSITION A.4:** *If the capacity constraint is binding and timber trade restrictions cause the same absolute price reduction for all tree qualities, the incentives for a marginal agricultural expansion remain unchanged.*

*Proof:* When the capacity constraint is binding, closing down a single field will not affect the total harvest ( $\sum_i H_0^i = \sum_i H_{-1}^i$ ). Nor will the total harvest be affected by timber trade restrictions (Proposition A.1). Furthermore, when timber trade restrictions reduce all timber

prices by the same absolute amount (i.e., when  $\tilde{p}(H, \alpha) = k\alpha + \hat{p}(H)$ ), trade restrictions do not change the relative marginal profit between fields. Hence,  $dH_0^i/d\alpha = dH_{-1}^i/d\alpha = 0, \forall i$ . From Eq. (26) we then obtain  $d\hat{\pi}/d\alpha = \sum_i (kH_0^i - kH_{-1}^i) = 0$ .